

# GOCE REENTRY PREDICTIONS FOR THE ITALIAN CIVIL PROTECTION AUTHORITIES

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## ABSTRACT

The uncommon nature of the GOCE reentry campaign, sharing an uncontrolled orbital decay with a finely controlled attitude along the atmospheric drag direction, made the reentry predictions for this satellite an interesting case study, especially because nobody was able to say a priori if and when the attitude control would have failed, leading to an unrestrained tumbling and a sudden variation of the orbital decay rate. As in previous cases, ISTI/CNR was in charge of reentry predictions for the Italian civil protection authorities, monitoring also the satellite decay in the frame of an international reentry campaign promoted by the Inter-Agency Space Debris Coordination Committee (IADC). Due to the peculiar nature of the GOCE reentry, the definition of reliable uncertainty windows was not easy, especially considering the critical use of this information for civil protection evaluations. However, after an initial period of test and analysis, reasonable and conservative criteria were elaborated and applied, with good and consistent results through the end of the reentry campaign. In the last three days of flight, reentries were simulated over Italy to obtain quite accurate ground tracks, debris swaths and air space crossing time windows associated with the critical passes over the national territory still included in the global uncertainty windows.

## 1. INTRODUCTION

The ESA's GOCE satellite was launched on 17 March 2009, at 14:21 UTC, from the Plesetsk cosmodrome, in Russia, on a Rokot launcher. It had a dry mass of 1002 kg and a roughly cylindrical shape of 1 m diameter and 5.3 m length, with wing-shaped fins spanning 2 m (Fig. 1). The minimum equivalent drag area was 1.0 m<sup>2</sup>, while the maximum lateral area was 11.2 m<sup>2</sup> [1]. After mapping the geopotential with unrivalled accuracy and detail for four years from an extremely low circular polar orbit, on 21 October 2013 the low thrust ion propulsion motor, used to contrast the atmospheric drag, was automatically shut down when the pressure in the xenon propellant tank dropped below a critical threshold. Then the satellite entered in Fine-Pointing Mode (FPM), a phase of orbital altitude decay with active fine attitude control carried out by a set of magnetotorquers.

According to the pre-launch specifications, the attitude control system was expected to compensate the gravity gradient and the aerodynamic torques up to an average drag force along the orbit of 20 mN. However, the system proved itself much more robust than envisaged, remaining operational until reentry, with drag forces perhaps exceeding 2000 mN, far beyond the levels the FPM controller was designed for.



Figure 1. Artistic representation of the GOCE satellite  
(Credit: ESA)

Therefore, even though the casualty expectancy for this reentry was just slightly above the internationally recognized alert threshold of 1/10,000, i.e. around 1/5000, it presented a number of challenges and opportunities, from the prediction and risk evaluation points of view, by reason of its peculiar nature. In actual fact, the instant and the altitude at which the attitude control system would have failed were unpredictable during the GOCE reentry, and ad hoc criteria had to be devised to define reasonable and conservative reentry uncertainty windows. This paper outlines the main difficulties encountered and the solutions adopted to accomplish our objectives. It highlights in particular the importance of a set of tailored products developed for the Italian civil protection authorities to identify, a few days ahead of reentry and in wide areas of interest, risk zones and corresponding alert time windows in the event of undue debris impact hazard on the national territory.

## 2. RISK ASSESSMENT AND RISK TIME WINDOWS FOR ITALY

GOCE represented the first uncontrolled reentry of an ESA satellite in more than 25 years. An ESA sponsored pre-launch destructive analysis had been carried out for it by Hyperschall Technologie Göttingen (HTG) using the Space-Craft Atmospheric Re-entry and Aerothermal Break-up (SCARAB) software tool [2]. It had predicted that, during the uncontrolled atmospheric reentry, the beginning of the satellite fragmentation would have occurred around an altitude of 95 km and the end around 35 km, even if most of the debris generation would have been expected in between 80 and 45 km. Overall, 43 macroscopic pieces, totaling approximately 270 kg (i.e. nearly 27% of the satellite dry mass), should have survived reentry, hitting the ground along a 900 km footprint during a 17 minutes time interval. The most massive fragment would have had a mass just below 95 kg.

There were no hazardous materials on-board and, according to ESA, the components that were suspected to survive reentry were a tank and the magnetotorquers. The rest of the falling debris should have been just irregular fragments. Being the GOCE orbital inclination of  $96.55^\circ$ , i.e. its motion was retrograde with respect to the Earth rotation, all the places between  $83.5^\circ$  south and north were overflowed. This corresponded to more than 99% of the Earth surface, excluding only two small spherical segments around the north and south poles.

Even if not zero, the individual risk for any inhabitant of the Earth was very small: 65,000 times lower than being hit by lightning, or 1.5 million times lower than being killed in a home accident. Taking into account the scant public data available and the methodologies outlined in [3], we found a minimum casualty expectancy,  $E_C$ , associated with the event of nearly 0.0002, implying a probability of 1 casualty over the whole world of at least 1/5000.

According either to procedures detailed in [3] [4] [5], and to timing dispersion, in terms of airspace crossing and ground impact, of the expected surviving fragments, the boundaries of the risk time windows valid for the Italian territory and airspace, i.e. from the geodetic altitude of 12 km down to ground impact, were determined by subtracting 10 minutes (lower bound) and by adding 30 minutes (upper bound) to the simulated “fictitious” ground impact times of the intact satellite, conventionally assumed as reference to set the absolute scale of time. These 40 minutes risk time windows would have been adequate to cover the impact time dispersion of the expected macroscopic fragments (17 minutes), the time needed to cross the national airspace from 12 km down to the ground, the trajectory and propagation uncertainties, and the probable

production of small slowly descending particles, not modeled by SCARAB, but possibly representing a marginal hazard for aircraft in flight.

## 3. THE PECULIAR NATURE OF THE GOCE REENTRY CAMPAIGN

After depletion of the xenon fuel for the drag compensating ion propulsion system, on 21 October 2013 the mission came to a natural end and GOCE began its orbital decay phase from a height of about 225 km. Its orbital evolution until the final reentry was monitored at ISTI/CNR in the framework of the GOCE international campaign promoted by the Inter-Agency Space Debris Coordination Committee (IADC). Contextually, output products tailored for civil protection applications by the Italian national authorities were devised and delivered.

According to ESA information, once the fuel ran out, GOCE entered in fine-pointing mode, the normal operational mode assumed during the orbital decay as a result of the satellite’s aerodynamic shape and fine active attitude control, which enabled GOCE to enter a more stable configuration, instead of the typical tumbling exhibited by most uncontrolled reentering spacecraft. During this phase the satellite maintained a stable attitude, minimizing the drag force, with a product of drag area ( $A$ ) and drag coefficient ( $C_D$ ) around  $3.5 \text{ m}^2$  [1].

In conformity with the pre-launch specifications, the on-board attitude control system was expected to compensate the gravity gradient and the aerodynamic torques until an average drag force along the orbit of 20 mN was reached [1]. At this point the attitude control would have failed, making the reentry of GOCE totally uncontrolled, and, according to simulations carried out by ESA (a 6 degrees of freedom analysis using SCARAB to investigate the aerodynamic properties after the end of the FPM phase), GOCE would have probably assumed a random tumbling attitude, with a corresponding  $A \times C_D = 11 \text{ m}^2$  [1]. With such an attitude and the prevailing thermospheric conditions, the satellite should have remained in orbit for a few days after the end of the FPM phase.

However, contrarily to any expectation, the attitude control system kept working until reentry, even when the drag levels encountered exceeded 2000 mN, i.e. far beyond (more than 100 times) the project specifications. According to the ESA report on the “GOCE end-of-mission operations”, the “spacecraft operations proceeded up to 1.5 hours before reentry, with the last ground contact at KSAT’s Troll Station in Antarctica on 10/11/2013 at 22:43 UTC” [6]. The most surprising fact was that the attitude control in FPM was still operational.

#### 4. EVOLUTION OF THE DRAG FORCE

The evolution of the drag force on GOCE was computed at ISTI/CNR using an upgraded version of the SATellite Reentry Analysis Program (SATRAP) software tool [7] and assuming a fine-pointing attitude control. Fig. 2, issued together with the first ISTI/CNR reentry prediction on 23 October 2013, shows the results obtained with two standard atmospheric density models, the Russian GOST-2004 [8] and the American NRLMSISE-00 [9]. Both models predicted the reaching of a mean drag force of 20 mN along the GOCE orbit around 1-2 November 2013, but the exact moment when the satellite attitude control system would have been overwhelmed by the harsh environmental conditions was totally unforeseeable, as demonstrated by the very impressive and unexpected FPM performances. Considering the very good agreement between the two atmospheric density models, for practical reasons only one of them (NRLMSISE-00) was used during the GOCE reentry campaign. Fig. 3 shows the altitude evolution above the reference Earth ellipsoid corresponding to the expected drag force, as of 23 October 2013 (Fig. 2).

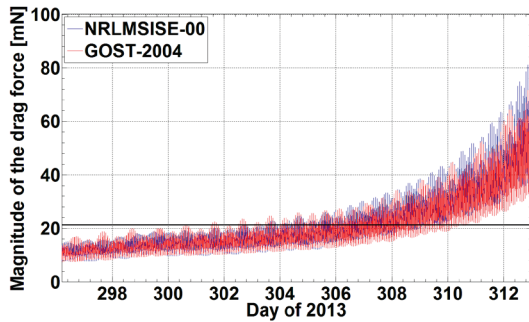


Figure 2. Predicted evolution of the magnitude of the drag force on GOCE assuming an operational FPM (NRLMSISE-00 & GOST-2004, 23 October 2013)

The knowledge of the drag force evolution, with particular attention to the epoch associated with an average drag force along the orbit expected to overcome the FPM controller, or that corresponding to the earlier onset of a peak drag force with the same magnitude, was of value to elaborate reasonably conservative criteria for the early definition of the reentry uncertainty windows. For instance, in the so-called “test and analysis phase” of the reentry campaign (23-31 October 2013), the opening of the reentry window was computed by assuming the loss of the FPM attitude control at the onset of a 20 mN peak drag force, while the nominal reentry time was predicted considering the loss of FPM after the reaching of an average drag force of 20 mN. In both cases, the spacecraft was considered to be random tumbling, with  $A \times C_D = 11 \text{ m}^2$ , afterwards. Eventually, the closure of the reentry window was obtained under the hypothesis of a FPM active until the very end.

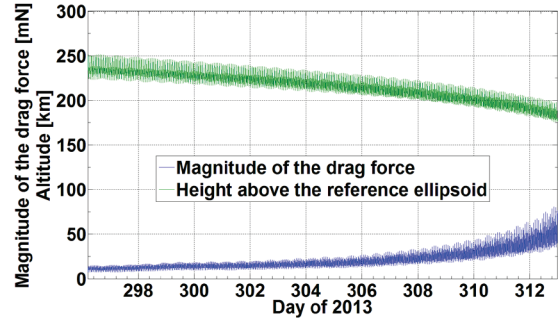


Figure 3. Predicted evolution of the magnitude of the drag force (NRLMSISE-00) on GOCE and of the satellite height above the reference ellipsoid (issued on 23 October 2013)

The constant monitoring all over the reentry campaign of the drag levels encountered permitted either to verify the very impressive performance of the GOCE attitude control system and to test the goodness of the simulation results obtained with NRLMSISE-00. A very good agreement was found between measured (plots provided by ESA, for the instantaneous drag and the average drag over one orbit, through the IADC Reentry Events Database) and simulated drag force, proving that even when it exceeded 20 mN, the satellite kept working in FPM. Successive simulations showed that, at the beginning of 8 November 2013, the mean drag force exceeded 50 mN (Fig. 4), coming near to 100 mN on 10 November (Fig. 5), and exceeding 1000 mN a few hours ahead of reentry (Fig. 6).

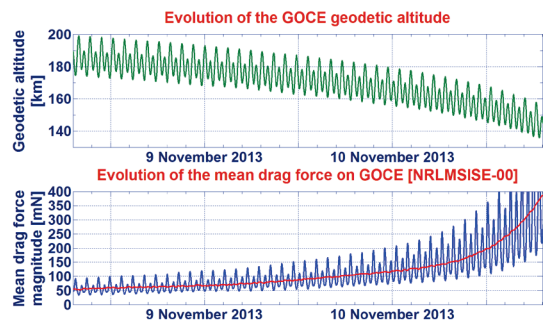


Figure 4. Predicted evolution of the magnitude of the drag force on GOCE and of the satellite height above the reference ellipsoid (issued on 8 November 2013)

The evolution of the drag force encountered by the satellite just before reentry was also estimated, in a post-event analysis, using the thermospheric density model JB2008 [10]. Fig. 7 shows the magnitude of the drag force simulated with NRLMSISE-00, GOST-2004 and JB2008, starting from half a day before the final orbital decay. Apart from the observation of a very good agreement among the outputs obtained by different atmospheric density models, the results displayed once

again the extraordinary level of over-performance of the attitude control system, still working at drag levels of more than 1000 mN, and operational until reentry, with limiting drag forces probably exceeding 2000 mN.

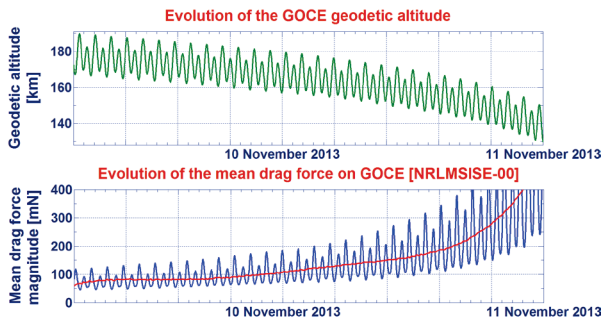


Figure 5. Predicted evolution of the magnitude of the drag force on GOCE and of the satellite height above the reference ellipsoid (issued on 9 November 2013)

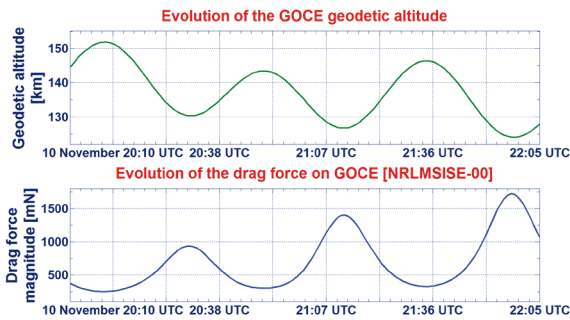


Figure 6. Predicted evolution of the magnitude of the drag force on GOCE and of the satellite height above the reference ellipsoid (issued on 10 November 2013)

## 5. THE REENTRY PREDICTIONS CAMPAIGN

Overall, 22 reentry predictions were carried out for the GOCE reentry campaign. The first was issued by ISTI/CNR on 23 October 2013, followed by six others performed during the so-called “test and analysis phase” (23-31 October 2013). Predictions 8-14 were issued during the “operational phase” (2-8 November 2013), while predictions 15-22 were carried out in the “final phase” (9-10 November 2013).

Each reentry prediction involved the following computational tasks:

1. Estimation of the product  $A \times C_D$ , by minimizing the root mean square residuals between observed (Fig. 8) and computed mean semi-major axis decay;
2. Propagation of the last available Two-Line Elements (TLE) set, using the estimated  $A \times C_D$ , to assess the

evolution of the drag force acting on the satellite under the assumption of an operational fine-pointing mode;

3. Computation of the “nominal” reentry epoch, based on a set of hypotheses evolving in accordance with the new data available on the performance of the attitude control system;
4. Definition and computation of a global reentry uncertainty time window associated with each reentry prediction;
5. Representation of the ground tracks corresponding to the current global uncertainty time window, during the last 3 days before reentry.

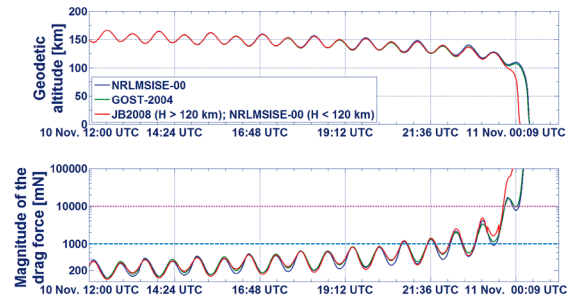


Figure 7. Evolution of the magnitude of the drag force on GOCE and of the satellite height above the reference ellipsoid in the 12 hours ahead of reentry (post-event analysis)

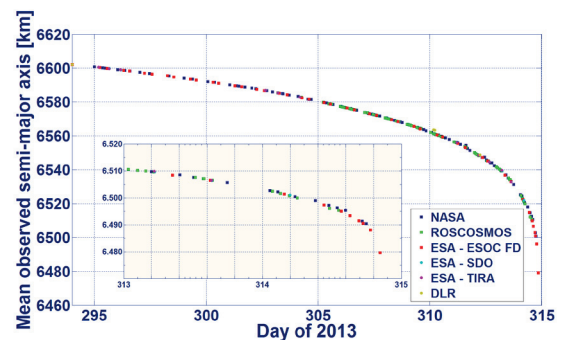


Figure 8. Observed mean semi-major axis decay of GOCE, from 21 October 2013 to the last orbital elements before reentry, inferred from the US, Russian, ESA and DLR two-line elements acquired from the IADC Reentry Events Database, maintained at ESA/ESOC

### 5.1. Products for Civil Protection Applications

Nevertheless, the aforementioned reentry predictions standard products, i.e. the nominal decay forecast, the global uncertainty time window and the sub-satellite ground tracks included in the latter, were of no, or very limited, use for civil protection applications.

As a matter of fact, the large intrinsic uncertainty

affecting the nominal decay forecast made it absolutely useless for civil protection planning. The global uncertainty time window provided instead relevant information, identifying the time interval in which the reentry could be expected, somewhere in the world. But this interval remained too large until reentry, so it was not possible to devise and apply practical precautionary civil protection measures based on it. Moreover, inside the global uncertainty window, the reentry location remained quite undetermined, along a varying number of orbital sub-satellite tracks, themselves possibly affected by a considerable cross-track error. Therefore, the locations possibly at risk in a given area embracing Italy could not be identified reasonably ahead of reentry with such information.

To solve these problems, a novel targeted approach was devised, implemented and applied in Italy to real reentry campaigns since the orbital decay of the BeppoSAX satellite in 2003 [11] [12] [13]. The same method was employed as well during the GOCE campaign and consisted in making available, 3 days ahead of the final decay, the possible reentry ground track, the associated risk zone (up to a given altitude) and the risk time window for each reentry opportunity over Italy included in the current global uncertainty time window. Providing such information a few days in advance was necessary to make possible the appropriate civil protection planning in the areas potentially affected and the reliable identification of the areas excluded from any risk.

But did this information maintain its accuracy and stability up to the very end? Even if conceptually difficult to explain, our approach was based on the simple remark that for each overflowed location included in the global uncertainty time window, reentry or debris ground impact was possible, in principle, but not certain; however, in each place, the eventual reentry or impact would have occurred only during a specific and quite accurate risk time window. The latest was then used to plan risk mitigation measures on the ground and in the overhead space and maintained its intrinsic accuracy until reentry.

The amplitude of the risk time window for Italy was mainly a function of the different flight times of the fragments able to survive reentry and hit the ground, accounting as well for minor errors affecting the trajectory propagation and initial conditions as, for instance, the finite size of the chosen area of interest including Italy [5]. Instead, the reference to set the absolute scale of time was assumed to coincide with the “fictitious” ground impact time of the intact satellite. This means that for each reentry opportunity over the national territory, included in the current global uncertainty time window, the ground impact time of the

simulated intact satellite was predicted first, and then the risk time window was defined with respect to this time, i.e. by subtracting 10 minutes and by adding 30 minutes to the reference time thereof [3] [4] [5].

The impact opportunities over Italy during the current global uncertainty time window were identified by iteratively modifying by a small amount the nominal product of the terms used to model the aerodynamic drag, i.e. drag coefficient, satellite cross-sectional drag area and atmospheric density, for instance by varying either the drag coefficient or the cross-section, inside their expected variation range. The reason of this approach was a consequence of the fact that the trajectory propagation uncertainty, leading to the comparatively wide global uncertainty time window, was dominated by the drag mismodeling and then the possible variations of the reentry time inside the uncertainty window were just the consequence of the possible variations of the atmospheric drag. The computed intact impact time, corresponding to each reentry opportunity over the Italian territory, resulted to be very accurate and also the cross-track errors in the corresponding sub-satellite ground tracks, expected up to satellite decay, canceled out to less than a few tens of kilometers. These results were the direct consequence of the almost exact synchronization of the satellite dynamical evolution and Earth rotation, in such a way to obtain a reentry just over Italy.

Moreover, considering a region sufficiently wide to include Italy and a significant portion of the surrounding lands and seas (e.g. almost  $2000 \times 2000 \text{ km}^2$ ), each possible reentry track was accurately modeled by simulating just one ground impact, with a maximum timing error of  $\pm 2$  minutes [5], deemed acceptable if compared with the flight times dispersion of the macroscopic fragments.

## 5.2. Global Reentry Uncertainty Windows

Due to the active control system and to the unpredictability of the instant and altitude at which the system would have failed, it was not possible to adopt standard criteria, based on previous experiences (e.g. by varying the residual lifetime or the satellite ballistic parameter – i.e. the product of area-to-mass ratio and drag coefficient – by, for instance,  $\pm 20\%$ , or more) to define the uncertainty reentry windows. However, after an initial period of test and analysis till the end of October 2013, in which only the opening of the window was of importance, to at least exclude an early reentry before a given epoch, reasonable conservative criteria were elaborated and applied, with good and consistent results through the end of the campaign. They were mainly based on the uncertainty affecting the duration of the FPM flight phase and depended as well on the information received by ESA and the acquaintance

gained meanwhile through the monitoring of the drag levels and satellite orbital decay.

During the test and analysis phase (23-31 October 2013), the conservative opening of the reentry window was obtained by propagating, up to the IADC reentry conventional altitude of 10 km, the orbit corresponding to the earliest onset of a peak drag force of 20 mN, assuming the loss of attitude control and  $A \times C_D = 11 \text{ m}^2$ . The definition of the window closure changed instead during this phase, trying to restrain it in order to reduce the time interval of interest. In the operational phase (2-8 November 2013), the conservative start of the reentry window was computed by assuming an immediate stop of the FPM and then a sudden random tumbling with  $A \times C_D = 11 \text{ m}^2$ . For the closure, the FPM was considered to be active until the very end, with the estimated  $A \times C_D$  reduced by 10-15%, in order to take into account a possible decrease of the drag coefficient at lower altitudes, characterized by quite shorter mean free molecular paths in the atmosphere. In the final phase (9-10 November 2013), and only for the last six predictions, standard criteria to define the uncertainty window, varying by a given percentage the product  $A \times C_D$ , were instead applied, as shown in Fig. 9.

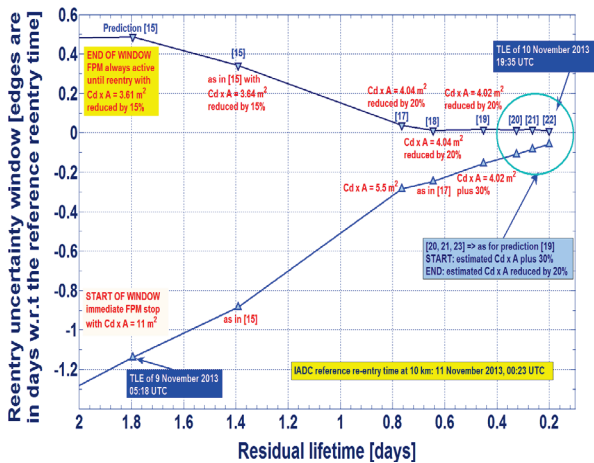


Figure 9. Final reentry uncertainty time windows during the last two days ahead of reentry

### 5.3. Estimated Nominal Reentry Epoch

Due to the significant uncertainty surrounding the end of the FPM flight phase, the nominal reentry forecasts were highly speculative, just a guess exercise. As shown in Tab. 1, the nominal reentry epoch for predictions 1-16 was obtained by propagating the orbit corresponding to the onset of the average drag force expected to cause the FPM stop, e.g. 20 mN for prediction 1, 150 mN for prediction 16. Instead, only the last six nominal reentry times (predictions 17-22) were computed with no assumption on the duration of the FPM phase, but just

propagating the last available orbital elements with the estimated  $A \times C_D$ . The evolution of the GOCE  $A \times C_D$  product during the reentry campaign is shown in Fig. 10. It was obtained with the ISTI/CNR software tool CDFIT, using the thermospheric density model NRLMSISE-00.

Table 1. Estimated nominal reentry epoch (intact object at 10 km, according to IADC convention)

Prediction number	Average drag force leading to FPM failure [mN]	Nominal reentry epoch	
		yyyy-mm-dd	hh:mm:ss [UTC]
1	20	2013-11-08	16:03:00
2	20	2013-11-04	22:05:45
3	20	2013-11-04	19:59:16
4	20	2013-11-04	11:11:07
5	20	2013-11-04	11:35:00
6	20	2013-11-04	16:38:59
7	20	2013-11-04	10:04:57
8	30	2013-11-07	05:54:50
9	30	2013-11-07	05:34:17
10	35	2013-11-07	21:50:16
11	45	2013-11-08	20:56:43
12	100	2013-11-10	11:16:14
13	150	2013-11-10	20:53:30
14	150	2013-11-10	13:10:13
15	150	2013-11-10	16:15:47
16	150	2013-11-10	15:07:08
	$A \times C_D [\text{m}^2]$	yyyy-mm-dd	hh:mm:ss
17	4.04	2013-11-10	21:37:15
18	4.04	2013-11-10	21:40:56
19	4.02	2013-11-10	22:34:00
20	3.93	2013-11-10	23:13:00
21	3.76	2013-11-10	23:32:00
22	3.74	2013-11-10	23:43:00

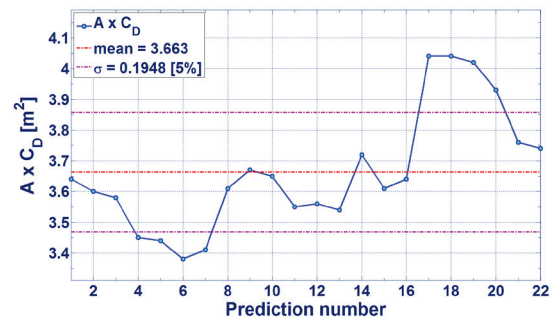


Figure 10. Estimated evolution of the GOCE ballistic coefficient ( $A \times C_D$ ), obtained with the ISTI/CNR CDFIT software tool and the atmospheric density model NRLMSISE-00

Being the difference between the mean estimated value of the ballistic coefficient ( $A \times C_D = 3.663 \pm 0.195 \text{ m}^2$ ) and the corresponding value computed for the FPM phase ( $A \times C_D = 3.5 \text{ m}^2$ , according to ESA analyses)

within the standard deviation ( $\pm 5\%$ ), the GOCE reentry campaign offered as well the opportunity to gain insight into the accuracy of the air density model used, confirming very good performances of NRLMSISE-00 also for altitudes below 200 km, at least with the solar and geomagnetic conditions prevailing during the exercise.

#### 5.4. Parametric Evaluation of Nominal Reentry Epochs

Detailed parametric analyses were carried out during the GOCE reentry campaign (issued on: 31 October, 5, 7 and 9 November 2013) to explore the full set of possibilities, including also very low probability outcomes, according to the available information received from ESA. From all these analyses, it was evident the extreme sensitivity of the nominal reentry epoch to the exact value of the drag force able to overwhelm the GOCE attitude control system, as detailed in Tab. 2, issued on 31 October 2013. See also [14] [15] for more details.

*Table 2. Parametric evaluation of the intact nominal reentry epoch at 10 km (IADC convention), as a function of the drag level causing the FPM failure (issued on 31 October 2013)*

FPM failure	Nominal reentry epoch at 10 km
Immediate	3 Nov. 2013, 15:22 UTC
20 mN	4 Nov. 2013, 10:05 UTC
21 mN	4 Nov. 2013, 22:17 UTC
22 mN	5 Nov. 2013, 18:14 UTC
23 mN	6 Nov. 2013, 05:06 UTC
24 mN	6 Nov. 2013, 13:23 UTC
25 mN	6 Nov. 2013, 20:00 UTC
30 mN	7 Nov. 2013, 20:47 UTC
40 mN	9 Nov. 2013, 00:32 UTC
45 mN	9 Nov. 2013, 10:11 UTC
50 mN	9 Nov. 2013, 18:11 UTC
Always active	11 Nov. 2013, 12:40 UTC

#### 5.5. Possible Reentry Opportunities over Italy

In the last three days preceding the final reentry, the attention was focused on a specific area of the planet embracing Italy, so as to allow the civil protection authorities to plan and prepare appropriate risk mitigation measures for the zones potentially affected by a debris fall. This was realized by simulating reentries over the area of interest, in order to obtain quite accurate ground tracks, debris swaths and air space crossing time windows associated with the critical passes over the national territory still included in the current global uncertainty windows. The risk zones and time windows for Italy were first issued around 61 hours ahead of reentry. At that time the global uncertainty window was 67 hours wide and there were still six

reentry opportunities possibly affecting the Italian territory, each with an associated risk time window of 40 minutes, including the airspace crossing, from 12 km to ground impact (Tab. 3).

*Table 3. Reentry opportunities over Italy still included in the global uncertainty window 61 hours ahead of reentry (issued on 8 November 2013, 11:30 UTC)*

No.	Day	Opening	Closure
1	9 Nov. (descending)	06:37 UTC	07:17 UTC
2	9 Nov. (ascending)	17:55 UTC	18:35 UTC
3	10 Nov. (descending)	07:26 UTC	08:06 UTC
4	10 Nov. (ascending)	18:44 UTC	19:24 UTC
5	11 Nov. (descending)	06:48 UTC	07:28 UTC
6	11 Nov. (ascending)	18:10 UTC	18:50 UTC

Based on the information available, implying a maximum cross-track dispersion of the macroscopic fragments of  $\pm 15$  km, and taking into account the uncertainty surrounding the actual endurance of the spacecraft active attitude control system, in addition to the possible cross-track reentry trajectory errors and wind effects on the smallest relevant particles, an initial, and very conservative, ground safety swath of  $\pm 200$  km around the computed reentry tracks was assumed. Approaching the orbital decay, as the global uncertainty window underwent its natural contraction, the number of reentry opportunities over Italy was progressively reduced to four at minus 56 hours, to three at minus 40 hours and to only two at minus 25 hours, when the global uncertainty window had shrunk to 23.5 hours. The last opportunity (No. 4 in Tab. 3, shown in Fig. 11) was finally excluded 14 hours before reentry, thanks to a significant contraction (to  $\pm 120$  km) of the ground safety swath, which previously had included north-western Italy, close to the border with France, and western Sardinia.

#### 5.6. Final Global Reentry Ground Track

The final global ground track associated with the last reentry prediction uncertainty was issued by ISTI/CNR to IADC approximately 4 hours before reentry (Fig. 12). The GOCE fragments eventually plunged into the Southern Atlantic Ocean, between the Falkland Islands and the coast of Argentina, on 11 November 2013, between 00:24 and 00:40 UTC.

## 6. CONCLUSIONS

The GOCE reentry prediction campaign was quite peculiar, because the satellite attitude was controlled, and it was not possible to predict a priori if and when the system would have failed. Having known since the beginning the extraordinary level of over-performance of the attitude control system, the nominal reentry epoch would have been consistently predicted with a much better residual percentage error.

However, being charged with civil protection responsibilities, much more important was the definition of consistent and conservative uncertainty windows. After an initial analysis phase, in order to test the suitability and reliability of the uncertainty windows definition, reasonably conservative criteria were elaborated and applied, with good and consistent results through the end of the campaign. Based on the progressively shrinking global uncertainty window, the last, quite marginal, reentry opportunity over Italy was finally excluded 14 hours before reentry and the GOCE surviving debris, according to the latest observations, sank into the Southern Atlantic Ocean, between the Falkland Islands and the coast of Argentina.

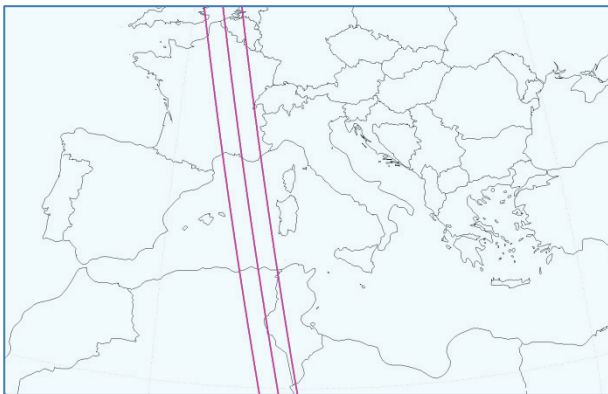


Figure 11. Last reentry opportunity (No. 4 in Tab. 3) grazing Italy (ascending central track): it was excluded 14 hours before the satellite decay when the cross-track safety swath defining the risk zone shrank to  $\pm 120$  km

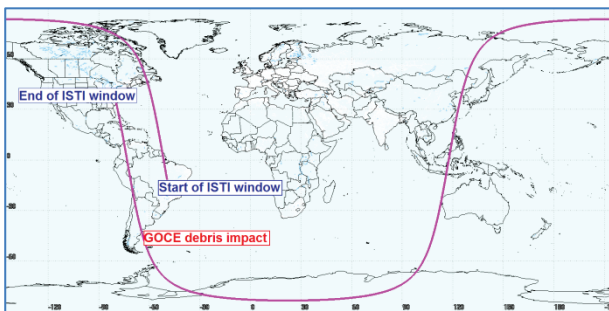


Figure 12. Global ground track associated with the reentry uncertainty corresponding to the last prediction (No. 22) and orbit of 10 November 2013, 19:35 UTC

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